"Identification of space-time flash flood vulnerability factors and indicators based on the analysis of impact data"

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IDENTIFICATION OF SPACE-TIME VULNERABILITY FACTORS AND INDICATORS BASED ON THE ANALYSIS OF IMPACT DATA

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ABSTRACT

Flash floods are short-term events, occurring within 6 hours of the causative event (heavy rain, dam break, levee failure, snowmelt and ice jams) and often within 2 hours of the start of high intensity rainfall. The rapidness of the flash flooding makes it difficult to be forecasted in adequate warning lead times. This fact exacerbates the surprising nature of the event and puts more people and property at risk. Of course, flash flood can affect everyone and everything. But why not everyone experience the event in the same way? Vulnerability is a concept evolved out of the social sciences to explain the contextual human factors that can alter the scale and social distribution of impacts. Unfortunately, flash flood monitoring and prediction tools (e.g. distributed hydrologic models) do not incorporate social origin aspects. In this study, a critical analysis of previous flood impact and vulnerability studies is conducted in order to deeper understand the human-related concepts that determine the flash flood severity. The main output of the analysis is the development of a conceptual model for assessing vulnerability to flash flood. Based on this model, a comprehensive set of potential variables for the measurement of vulnerability to flash floods is proposed. Further questions are then arising: How the specific characteristics of the human and the built environment contribute to the increase or decrease of the local vulnerability within the flash flood temporal and spatial scale? Is this contribution always the same? The most important advance of the current research in comparison with previous efforts in vulnerability measurement and mapping is the introduction of the concept of the spatial and temporal variability of vulnerability. This means that vulnerability is not considered as a static picture/evaluation of a place or system but as an ever evolving process built from the interaction of social and physical dynamics. To complete the study, a computational model capable to incorporate the dynamic nature of vulnerability to flash flood is proposed. Finally, limitations and uncertainties are discussed and future challenges are presented. The integration of a spatial vulnerability model and a hydrologic prediction model should be the ideal prospect of the current research in the future in order to identify vulnerable targets and mitigate the subsequent impacts of flash floods.

Keywords: flash floods; impacts; spatio-temporal vulnerability assessment; vulnerability model

ΠΕΡΙΛΗΨΗ

Οι ξαφνικές πλημμύρες είναι βραχυπρόθεσμα γεγονότα, που συμβαίνουν εντός 6 ωρών από την εκδήλωση των βαθύτερων αιτιών τους (π.χ. έντονη βροχή , θραύση φράγματος ή αναχώματος, σύνθλιψη χιονιού ή πάγου), ενώ συνήθως εκδηλώνονται μέσα σε 2 ώρες από την έναρξη της έντονης τοπικής βροχόπτωσης. Η έγκαιρη πρόβλεψη αυτού του τύπου πλημμύρας καθίσταται ιδιαίτερα δύσκολη λόγω της μεγάλης ταχύτητας και της μικρής χωρικής κλίμακας που χαρακτηρίζουν την εμφάνισή του. Δεδομένου ότι συμβαίνουν ξαφνικά και με ελάχιστη προειδοποίηση, οι στιγμιαίες πλημμύρες είναι ιδιαίτερα επικίνδυνες για τους ανθρώπους και τις ιδιοκτησίες. Φαινομενικά, το πλημμυρικό επεισόδιο μπορεί να επηρεάσει τους πάντες και τα πάντα. Αλλά γιατί δεν βιώνουν όλοι το ίδιο γεγονός με τον ίδιο τρόπο; Η ευπάθεια είναι μια έννοια που εξελίχθηκε από τις κοινωνικές επιστήμες για να εξηγήσει τους συναφείς ανθρώπινους παράγοντες που μπορούν να αλλάξουν την κλίμακα και την κοινωνική κατανομή των επιπτώσεων. Δυστυχώς, τα εργαλεία ελέγχου και πρόβλεψης των ξαφνικών πλημμυρών (π.χ. κατανεμημένα υδρολογικά μοντέλα) δεν ενσωματώνουν πτυχές κοινωνικής προέλευσης. Σε αυτή τη μελέτη, πραγματοποιείται μία εκτεταμένη κριτική ανάλυση προηγούμενων μελετών σχετικά με τις επιπτώσεις των πλημμυρών. Στόχος είναι η βαθύτερη κατανόηση των ανθρωπογενών παραγόντων που καθορίζουν την δριμύτητα των ξαφνικών πλημμυρών. Το κύριο προϊόν της ανάλυσης είναι η ανάπτυξη ενός θεωρητικού μοντέλου για την εκτίμηση της ευπάθειας σε ξαφνική πλημμύρα. Με βάση το μοντέλο αυτό, προτείνεται ένα ολοκληρωμένο σύνολο πιθανών μεταβλητών για τη μέτρηση (ποσοτικοποίηση) της ευαισθησίας σε ξαφνικές πλημμύρες. Περαιτέρω ζητήματα προκύπτουν στη συνέχεια: Πώς τα ειδικά χαρακτηριστικά του ανθρώπινου και του δομημένου περιβάλλοντος συμβάλλουν στην αύξηση ή τη μείωση της τοπικής ευπάθειας στο πλαίσιο της χρονικής και χωρικής κλίμακας που χαρακτηρίζει την ξαφνική πλημμύρα; Είναι η συμβολή αυτή πάντοτε σταθερή; Η σημαντικότερη πρόοδος της παρούσας έρευνας σε σύγκριση με τις προηγούμενες προσπάθειες στη μέτρηση και χαρτογράφηση της ευπάθειας είναι η εισαγωγή της έννοιας της χωρικής και χρονικής μεταβλητότητας της ευπάθειας. Αυτό σημαίνει ότι η ευπάθεια δεν θεωρείται ως μια στατική εικόνα / αξιολόγηση ενός τόπου ή συστήματος, αλλά ως μια διαρκώς εξελισσόμενη διαδικασία που χτίστηκε από την αλληλεπίδραση του δυναμικού κοινωνικού και φυσικού συστήματος, αντίστοιχα. Για την ολοκλήρωση της μελέτης, προτείνεται ένα υπολογιστικό μοντέλο ικανό να ενσωματώσει τη δυναμική φύση της ευπάθειας σε στιγμιαία πλημμυρικά γεγονότα. Τέλος, παρουσιάζονται οι περιορισμοί και οι αβεβαιότητες καθώς επίσης και οι μελλοντικές προκλήσεις στην εκτίμηση της ευπάθειας σε ξαφνικές πλημμύρες. Η ενσωμάτωση ενός χωρικού μοντέλου τρωτότητας (ευπάθειας) σε ένα υδρολογικό μοντέλο πρόβλεψης αποτελεί την ιδανικότερη προοπτική της τρέχουσας έρευνας στο μέλλον, προκειμένου να εντοπιστούν ευάλωτες περιοχές και πληθυσμοί και να αμβλυνθούν οι επακόλουθες συνέπειες των ξαφνικών πλημμυρών.

Λέξεις-κλειδιά: Ξαφνική πλημμύρα, επιπτώσεις, χωρο-χρονική εκτίμηση ευπάθειας, μοντέλο ευπάθειας

RESUME

Les crues éclair sont des évènements caractérisés par une montée rapide et soudaine des eaux, survenant dans les six heures qui suivent l'évènement déclencheur (fortes pluies, défaillance des barrages, effondrements de digues, fonte des neiges) et parfois dans les deux heures qui suivent des fortes précipitations. La rapidité de ces évènements complique leurs prévisions ce qui ne laisse pas le temps aux responsables pour avertir la population et accroit le risque lié à ce type d'évènements. Cependant, les crues rapides n'affectent pas les individus et les lieux de la même manière. La vulnérabilité est un concept développé dans les sciences sociales qui permet d'expliquer le rôle joué par les facteurs humains et contextuels dans l'étude des impacts de ces évènements. Cependant, les outils de prévision des crues rapides (e.g. les modèles hydrologiques distribués) ne prennent pas en compte la dimension sociale. Dans cette étude, on a conduit une analyse critique des travaux antérieurs sur la vulnérabilité et l'étude des impacts des crues en introduisant des concepts issus des sciences *sociales et humaines. L’objectif principal de ce travail est le développement d’un modèle conceptuel qui permet d’évaluer la vulnérabilité aux crues rapides. Sur la base de ce modèle, on propose un ensemble de variables potentielles pour mesurer la sévérité de ces évènements. D’autres questions seront ensuite posées: Comment les caractéristiques sociales et environnementales interviennent dans l’augumentation ou la diminution de la vulnérabilité locale aux crues rapides? Et est ce qu’elles interviennent toujours de la même manière? La contribution principale de cette étude par rapport aux travaux précédants sur la vulnérabilité consiste à mettre l’accent sur sa variabilité spatio temporelle. Ainsi la vulnérabilité n’est pas considérée comme une évaluation statique d’un lieu ou d’un système donné mais plutôt comme un processus en continuelle évolution basé sur l’interaction entre les dynamiques sociales et physiques. Ensuite, nous allons proposer un modèle computationnel capable d’intégrer le caractère dynamique de la vulnérabilité aux crues rapides. Enfin, nous allons examiner les limites et les incertitudes et présenter les persepectives futures de notre travail. L’intégration d’un modèle spatiale de vulnérabilité et d’un modèle hydrologique de prévision est l’objectif future de cette étude ce qui permet d’identifier les facteurs de vulnérabilités et d’atténuer l’impact des futures crues rapides.*

Mots clé: crues rapides; impact; évaluation spatio temporelle de la vulneérabilité; modèle conceptuel de vulnérabilité

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CONTENTS

1. INTRODUCTION

Flash flood is a specific type of flooding considered as “flood that rises and falls quite rapidly with little or no advance warning usually as the result of intense rainfall over a relatively small area” (AMS, 2000). This definition could explain the difficulty to predict flash floods and develop adequate warning systems capable to protect people and property. Indeed, despite the technological advance concerning the mapping and forecasting models capabilities, reducing the flash flood losses remains a challenge (Montz and Gruntfest, 2002). In the United States (US) 954 fatal accidents due to floods and flash floods have been recorded from 1995 to 2012[1]. For the same period, floods caused approximately 31 billion U.S. dollars of property damage across the United States. In the US flash flooding is the leading cause of weather related deaths every year, with some 200 annual fatalities[2]. Also, in Europe flash floods are the main responsible for the mortality although they affect smaller areas than riverine flooding (Jonkman, 2003). But what are the main drivers of flash flood consequences?

Since the 1970s it has been recognized that differences in losses related to natural hazards such as floods depend not only on the hazard severity but also on the social factors of the exposed regions (O’Keefe et al., 1976). Kelman (2004) states that disasters do not come out from the natural hazard itself but they result from the underlying vulnerability that is determined by the sociological and human-dependent circumstances. In other words, if a hazardous event like flash flood occurs in a remote area then there is no threat for harm at all. Consequently, if there are no impacts on human life and daily activities, and the surrounding built environment, then there is no interest to study the conditions leading to the natural phenomenon. Thus, it is argued that the impacts of flash flood events are driven from the natural and the built environment as well as the societal context and the individuals’ behavior (Montz and Gruntfest, 2002; Ruin et al., 2008). Particularly, it is the choices of development that are made by the society and their interactions with individuals’ decisions that define the built environment (location and type of buildings/infrastructure) and the characteristics of the exposed area (population density/ land cover/warning systems). In simple words, humans and their environment interact continually and shape each other rather than being separated parts (Wood, 2004). Thus, despite of the type of impacts (i.e. material or human damages) the scientific community generally agrees that the integrated study of natural event characteristics and the human-related concepts and attributes is necessary to understand the different aspects of vulnerability and lessen the most important impact: the loss of life (FLOODsite, 2005; Messner and Meyer, 2005; Ashley and Ashley, 2008; Jonkman et al., 2009). However, up to now there is very little work on the integrated study of vulnerability to flash floods and even fewer studies on the intersection of human behavior with flash flooding (Ruin et al., 2008).

This study seeks to enhance the knowledge about the human-related parameters that make individuals and infrastructure to experience flash flooding in a different way. An integrated conceptual model for the assessment of coupled physical-social vulnerability to flash flood is proposed, based on a critical analysis of flood impacts-related literature review. The study primarily focuses on a review of literature and

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[1] NOAA; US National Weather Service, http://www.statista.com/statistics/203709/number-of-fatalities-caused-by-floods-and-flash-floods-in-the-us/

[2] NOAA, http://www.weather.gov/pbz/floods

data from European, North American and Australian case studies. In addition to data availability, common features in terms of human development index and living conditions allow making parallels between Europe and North America and contribute to the applicability of this paper's findings on these regions. For example, we assume that similar economic conditions (i.e. high income countries) have similar ability to assign financial resources to flood risk forecast, mitigation and protection strategies. The ability of high income countries for more advanced flood risk prevention and management could explain the fact that although they are affected more frequently by natural catastrophes they are characterized by fewer fatalities (Jonkman, 2005). Three basic assumptions are made concerning the developed economies with high income per capita (> 11.906 GNI US $/ capita):

- Similar strategies on natural hazards and risk governance.
- Similar potentiality to produce flood forecasting and warning systems.
- Similar type and level of flood impacts.

The fundamental questions that arise through the present analysis are the following:

1. How does the type of hazard (space and time scales) affect vulnerability and determine the level of flash flood impacts?
2. What are the human-dependent processes that are related to flash flood risk?
3. Which indicators can represent the social conditions reflecting the space-time variability of vulnerability to flash floods?
4. What actual data are available to serve as proxy variables of those indicators?
5. How to test the relevance of the selected indicators and proxies?

The first question is answered in section 2 through the development of a vulnerability framework within the flash flood spatial and temporal context. Section 2 provides also all the important definitions used in the present report and describes the methodology used. Section 3 discusses the second question and presents a conceptual model for the assessment of vulnerability to flash flood to explain the main vulnerability processes and the embedded functions. The three last questions are explored in section 4 with two main contributions. Firstly, the provision of a comprehensive set of relevant vulnerability indicators accompanied with a list of potential proxies (i.e. primary variables); and secondly, the introduction of a computational model to be used for the evaluation of the proposed variables (i.e. indicators and proxies). At this section, issues like the variability of vulnerability in time and space and the underlying uncertainties in the flash flood vulnerability assessment are further discussed. Finally, section 5 provides the concluding remarks and highlights the next research steps in the future.

2. FLASH FLOOD VULNERABILITY FRAMEWORK

2.1. Is Vulnerability to flash flood hazard-specific?

Vulnerability derives from the Latin word "vulnerare" (to be wounded) and describes the potential to be harmed physically and/or psychologically; a concept that evolved out of the social sciences and was introduced as a response to the purely hazard-oriented perception of disaster risk in the 1970s (Schneiderbauer and Ehrlich, 2004). The Risk-Hazard approach that tried to understand the hazard's impacts as a function of exposure to the hazard event (White, 1974; Burton et al., 1978) includes the obvious fallacy of ignoring the variability of the consequences due to the different nature and characteristics of the exposed subsystems (Cutter et al., 2009). But as incomplete as it is to consider the risk without considering the social component of the exposed system, it would also be overly simplistic to only consider the vulnerability component. Nevertheless, some scientists recognize vulnerability as an intrinsic characteristic of a system or element and examine it independently of the hazard (UN/ISDR, 2004; Cardona, 2004; Wisner, 2002). As reported in Jonkman (2005), the severity of impact varies not only with the place (territory) where the event happened but also with the type of hazard as shown by the difference in mortality rate between flood and flash flood. Vulnerability encompasses the exposure to a specific hazard and all the intrinsic traits of the exposed people and places (i.e. sensitivity and coping capacity) that pre-exist or are generated at the time of the event as revealed by the type of impacts. This means that once vulnerability to flash flood is duly assessed (and subsequently quantified) it could serve as a useful tool for the evaluation of the potential consequences of flash flood events on the exposed population and the surrounding physical or built environment.

2.1.1. Flash flood spatial and temporal context

The European Union (EU) Floods Directive (2007) defines a flood as a covering by water of land not normally covered by water. Flash floods are mainly distinguished from a regular flood in terms of timescale and spatial extent (Table 1). The National Weather Service Forecast Office defines a flash flood as a flood caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours. Flash floods are usually characterized by raging torrents after unusually heavy rains that rip through river beds, urban streets, or mountain canyons sweeping everything before them. They can occur within minutes or a few hours of excessive rainfall.

The type of flood is very important differentiating the type, the magnitude and the number of impacts (Jonkman, 2003; Ryan and Hanes, 2010; Vinet et al., 2012). As Jonkman (2005) observed from the study of the CRED disaster database, the difference between the two flood types not only contribute to shaping the type and degree of losses such distinct phenomena trigger but they also play a role in the emergence of specific forms of vulnerability that are not relevant in the case of general flooding.

Riverine Floods	Flash Floods
Exist in areas close to rivers	Can hit anywhere
The total rainfall amount drives the event	The rainfall intensity contributes to high flow rates
Need more than 6h to happen[3]	Need less than 6h (sometimes less than 1h) to occur
Occur usually in big catchments	Occur usually over small drainage area

Table 1. Flash floods attributes compared to river flooding.

The differences between the two types of flood presented in Table 1, have the following consequences in terms of vulnerability:

[3]Time between rainfall start and flooding occurence. Alternatively, it is the time between the peak of the rainfall and the flood peak.

1. In contrast with the river flooding where the proximity to streams and rivers indicate a potential risk level, the spatial variation of flash flooding occurrence inhibits the construction of flash flood zones. Therefore, the integration of flash flood risk in land-use planning does not constitute an applicable prevention measure. For this reason, other measures such as the development of advanced forecasting tools should be of higher consideration.

2. The small spatial and temporal scale that characterizes the phenomenon hinders the forecasting ability to predict the exact location of flash flooding with much warning lead time. Unlike riverine floods where extreme discharges can be predicted in advance, the accurate flash flood prediction is a big challenge. Although forecast and warning improvement are important issues in case of flash floods, the sudden onset nature of the hazard limits the available anticipation time of the population and increase the relative vulnerability.

An interesting point is that flash flooding can also occur even if no rain has fallen, for instance after a structural failure like the destruction of a levee or a dam[4]. Ashley and Ashley (2008) analyzed flood fatalities data from 1959 to 2005 in U.S. indicating more than 300 deaths from only nine dam and levee failures. Sometimes this type of flash flooding can be more catastrophic due to two reasons. Firstly, because of the difficulty to predict this failure and inform society; and secondly, because of surprising people who believe that being far away from the storm or behind a dyke keep them safe.

2.1.2. Flash flood Vulnerability definition

There are many definitions in the research literature for vulnerability, derived from different conceptual models and frameworks. Birkmann (2006) in his book presents a plethora of vulnerability definitions that are available on the current literature and highlights the existing paradox: scientists aim to measure vulnerability, without being able to give a precise definition yet. Therefore, in order to put a reasonable direction to our analysis a vulnerability framework has to be developed for this study (Figure 1). Based on Turner et al. (2003) vulnerability is defined as a function of three determinants: exposure, sensitivity, and coping capacity; a definition also used by Wilhelmi and Morss (2012) to analyse the societal vulnerability to a flash flood case study in Colorado.

The pre-mentioned studies illustrate a static view of vulnerability shaped by fixed characteristics of the natural event and the human environment. Turner et al. (2003) addresses the interaction of vulnerability with perturbations and the interrelations between the various spatial scales but do not take into account the time dimension. However, the three components of vulnerability all vary in space and time and therefore vulnerability shouldn't be considered as a static picture/evaluation of a place or system but as an ever evolving process built from the interaction of social and physical dynamics. In order to introduce the concept of variability of vulnerability in time and space two extra parameters are added to the aforementioned definition (Ruin, 2007).

[4] http://www.srh.noaa.gov/mrx/hydro/flooddef.php

Thus, the relationship that represents vulnerability to flash floods could take the following form:

$$Vulnerability = f\ (E;\ S;\ CC;\ t;\ s) \qquad (1)$$

where E is for Exposure, S for Sensitivity, CC for Coping Capacity ,t for time and s for space.

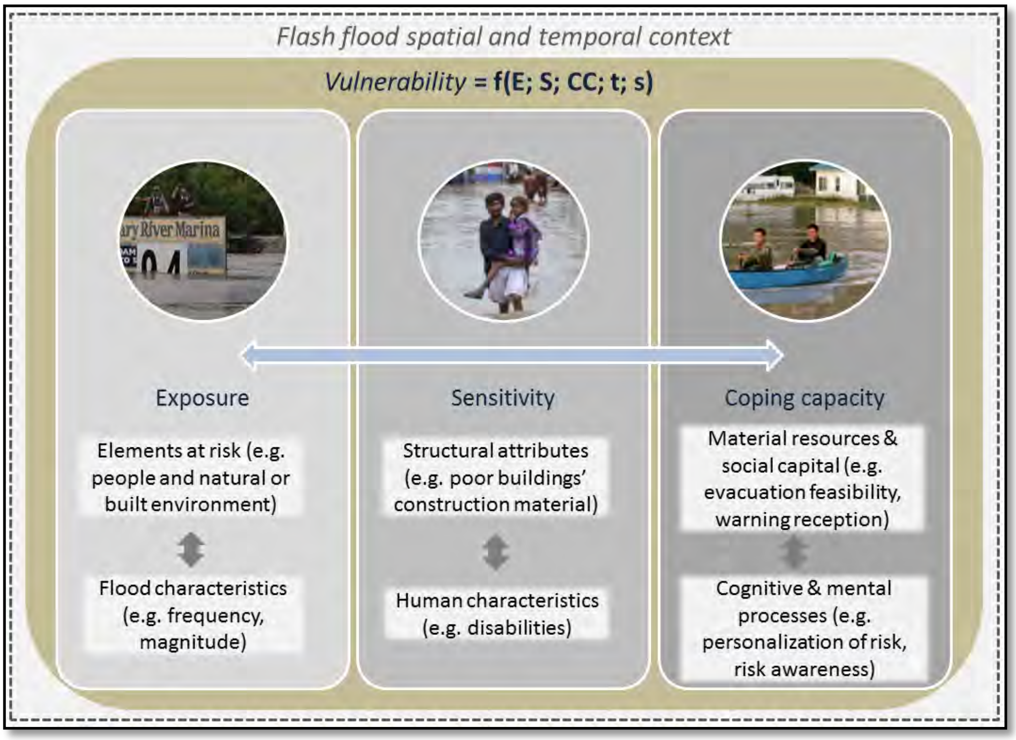


Figure 1. Flash flood Vulnerability framework.

Exposure: Exposure is defined as the intersection in space and time between a socio-ecological system (e.g. people and natural or built environment) and the occurrence of a threat of a specific nature and magnitude. Thus, it illustrates the complex relationship across space and time between the flood characteristics and the system under interest. Unlike previous studies that see exposure as an external feature that does not constitute a component of vulnerability (Bohle, 2001; Gallopin, 2003), here exposure is one of the vulnerability determinants.

Sensitivity: Sensitivity represents the pre-existing conditions of the exposed elements (e.g. people, buildings e.c.t.) that influence the degree to which the elements might be impacted. It is defined similarly to the concept of susceptibility as an intrinsic part of vulnerability (UN/ISDR, 2004). "Conditions" can refer to structural attributes of the built environment (e.g. poor buildings' construction material) as well as to human characteristics (e.g. disabilities due to old age or poor health) of the exposed system.

Coping capacity: Coping capacity is similar to the "coping ability" that is used in the literature to express short-term capacity or the ability to endure the strength of the perturbation (Smith and Wandel, 2006). Thus, coping capacity is differentiated from adaptive capacity that represents the longer-term ability of a system to respond to and recover from hazards (Adger, 2006). Coping capacity is mostly used to characterize individuals and human societies’ capability to deal with adverse conditions to avoid or lessen losses. This means that mitigation measures conducted at all levels (from individuals to institutions) are crucial parameters that drive the population coping capacity. Hence, the notion “capacity” poses a positive contribution to the reduction of vulnerability. Usually, coping capacity refers to material resources and social capital[5] that enable people to avoid being harmed. In addition to that, the current study introduces the mental and cognitive processes of individuals that intersect with the material resources and social capital and affect the way that people cope with the hazardous event. For example, the personal perception of risk is a mental process that could change the decision to evacuate independently of the availability of a car.

2.2. Flash flood Vulnerability Assessment Methodology

The flash flood vulnerability assessment can be divided in four sequent steps:

1. Forecast of extend and intensity of flash flooding (i.e development of a forecasting hydrologic model).
2. Identification of the factors and indicators that contribute to the space-time variability of the vulnerability (i.e. development of a conceptual model).
3. Estimation of vulnerability at the time and place of the forecasted occurrence (i.e. development of a mathematical-computational model).
4. Display of vulnerability and forecast of impacts (i.e. development of a visual spatial model).

The current study focuses on the second and third steps of the vulnerability assessment methodology setting the foundations for understanding the vulnerability to flash flooding. For localized and fast moving events such as flash floods where forecasting is problematic, indicators that incorporate the notion of vulnerability could enable identification of target areas where preventive measures are needed and decision-makers should focus.

2.2.1. Components of flash flood vulnerability analysis

In the literature, the term “vulnerability factor” is ambiguous. For example, it could refer either to the general human conditions or life circumstances (e.g. poor health or physical disabilities) (Cutter et al., 2000) of the vulnerable population or to a specific demographic characteristic related to these conditions (e.g. age) (Vinet et al., 2012). In addition to that, some studies name the pre-mentioned general conditions as “characteristics”, “concepts” or “indicators” (King and Macgregor, 2000; Priest et al., 2009). Others speak about the specific characteristics such as age or gender to

[5] The term “social capital” refers to social cohesion and personal investment in the community (Hanifan, 1916). In contrast with the material goods (i.e real estate or personal property), the social capital represents the intangible social intercourse among a group of individuals and families in the society. It terms of social vulnerability social capital would facilitate the mutually supportive relations in society and would therefore be a valuable mean of increased access to information and help during crisis. Thus, it is a resource for personal benefit derived from the web of social relationships and ties.

define specific vulnerability indicators (Tierney, 2001). To avoid misunderstandings, the paragraph below intends to clarify the terminology used in this paper.

In this study “factor” is a notion that is used to describe in a qualitative way the underlying physical conditions (e.g. the severity of the flood event) and physiological-psychological situations (e.g. physical disability to evacuate or risk-taking behavior of the population) that exacerbate the flood vulnerability.

The term “indicator” is related to more quantitative characteristics to measure or represent vulnerability to the catastrophic natural event (e.g. flood frequency, water depth, age, gender and profession). According to Cutter et al. (2009) Indicators are “quantitative measures intended to represent a characteristic or a parameter of a system of interest”. Thus, to address this definition numerical values and thresholds (e.g. surface runoff thresholds, % residents with disabilities and >75 yrs) are assigned to each indicator. These quantities are called “proxy variables”. Proxy variables enable vulnerability measurement and mapping.

Finally, to produce a map that synthesizes the level of vulnerability in an area under study, an index can be developed as a composite of more than one indicator.

2.2.2. Process for identification of flash flood vulnerability components

The process that is followed in the present study in order to identify the appropriate vulnerability indicators regarding flash floods is illustrated in Figure 2. As a first step the possible factors that influence vulnerability of places and people to flash flooding are explored through the review of the literature on flash flood fatalities and damages. On this stage questions like who or what is affected by a specific hazard event and what are the possible reasons leading to the casualty/amount of damage of this specific target could be answered. The output of this part is a conceptual vulnerability model capable to explain the dimensions of vulnerability to flash floods considered in the present study (see section 3).

In order to answer the critical question of what are the specific characteristics that draw vulnerability, factors have to be “converted” into specific indicators accompanied with proxy variables as second and third steps. These two steps are enforced (i) by a review of studies on assessment and mapping of vulnerability to different natural hazards using indicators and (ii) a critical analysis of the most relevant indicators and proxy variables used for the study of flash flood vulnerability. At this stage a comprehensive set of the proposed indicators and proxies is presented as the second output of our analysis. It has to be noticed that all this analysis is done considering the spatial and temporal scale of flash flooding (see the paragraph 2.1.1 for details on flash flood spatial-temporal characteristics). In addition to that, the variation on the different indicators in time and space is another issue that is analyzed through this study. Finally, a theoretical computational model for the measurement of vulnerability using the proposed indicators and proxies is developed. This model is designed according to the need for spatial and temporal dynamic representation of vulnerability to flash flooding (see section 4).

The process described above (Figure 2) is circular meaning that once the indicators and proxy variables are defined considering the related factors, vulnerability can be measured and mapped using the appropriate models and tools, and the possible impacts can be evaluated. In this way, this process is a valuable tool for prediction and forecasting approaches.

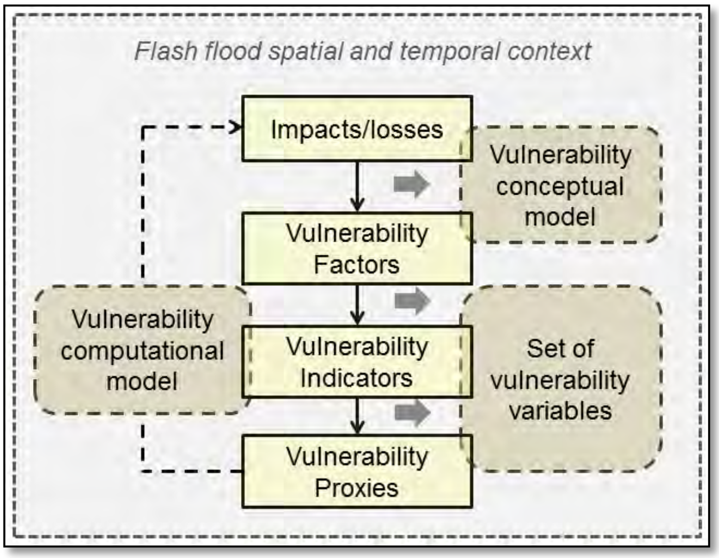


Figure 2. Process for the identification of flash flood vulnerability assessment components.

3. FLASH FLOOD VULNERABILITY FACTORS

3.1. Understanding of vulnerability through past-events impacts

Many researchers analysed the flood-related impacts of historic events (French et al., 1983; Coates, 1999; Ashley and Ashley, 2008; Sharif et al., 2012). Some studies that are related mainly to environmental and economic science focus on the tangible losses meaning the monetary damages (Sayers, 2002). In this case, the water depth is generally used to explain the amount of damage. Other social studies focus mainly on intangible losses (not expressed in monetary terms) like the loss of life or physical and mental health problems (Enarson, 2007). Usually, demographic characteristics (e.g. age, gender, e.c.t.) of the deceased people during a flood event are analyzed in order to explore the possible factors that made them susceptible to flooding (French et al. 1983; Coates, 1999; Ashley and Ashley, 2008). Given that most of the studies on flash flood fatalities are “event-specific” (Duclos et al., 1991; Vinet et al., 2011) generalizations are sometimes impossible. On the other hand, though the flood fatalities constitute only a subset of social or intangible effects, the only study of deaths to explore vulnerability is questionable. However, data availability concerning lethal consequences contributes to this trend (e.g. Storm Data reports from NCDC, NWS). Also, as Jonkman and Kelman (2005) state “although medical causes are not vulnerability factors in themselves, they are product of the amalgamation of hazard and vulnerability elements”. This section presents findings and statements from past studies on human flood losses that are useful for deeper understanding of place and population vulnerability. Unfortunately but logically, not all the available literature refers to flash floods. This contribution focuses on vulnerability circumstances that are related to direct impacts and damages produced during the emergency phase of the event. This means that for example, factors such as the poverty or the financial deprivation in terms of lack of insurance that lead to weak long-term recovery are not discussed in the present study.

3.1.1. Lessons learned from past flooding events

Flood casualties vary by region and the intensity of flooding. However, there are some commonly observed attributes. The main findings of the analysis of flood consequences on people life and property that drive our understanding of the possible vulnerability factors are:

1. Although sometimes it is difficult to distinguish the embedded phenomena, lethal consequences are related mostly to flash floods than river floods (Jonkman, 2005; Ashley and Ashley, 2008). Based on the analysis of 632 flood events reported in the OFRA/CRED International Disaster Database (EM-DAT) for the period 1975-2001, Jonkman (2005) shows that unlike riverine flood, flash flooding is characterized by a high mortality rate per event (5.6% versus 0.47% for riverine flooding). This finding is interesting considering the larger population and land areas affected by river floods in comparison with flash floods.

2. Drowning is the main cause of death in most of the past flood events especially when it is related with vehicle-mobility into flashing waters (French et al., 1983; Ryan and Hanes, 2010; Sharif et al., 2012; Diakakis and Deligiannakis, 2013). In case of flash floods water depth is not always high and therefore can be associated with less buildings collapses. Nevertheless, since the velocity of the water is usually very high it is much more dangerous for motorists and pedestrians[6]. According to FEMA (2010) only 0.15 m (6 in) of swift moving water can make a car driver to lose control and 0.61 m (2 ft) of water can carry away heavy vehicles.

3. Many flash flood fatalities happened together with the peak of the hydrological event (Ruin et al., 2008; Sharif et al., 2012) amplifying the important role of forecasting and warning. This means that many people die during the rapid rise of water-level and sometimes before the official warnings (Staes et al., 1994; Ruin et al., 2009).

4. Most of the flash flood impacts take place in the “event” phase (Duclos et al., 1991; Jonkman and Kelman, 2005). Insight in just before the flash flood (pre-event) and during the flooding circumstances is key to understand who/what experiences the event in the most disastrous way and why.

3.1.2. Exploring factors influencing vulnerability to flash flood

The severity of the flood event is the triggering factor for the property and human damages. Especially, it is the high flow rate (m/s) in case of flash floods that is responsible for sweeping away people, cars and property. The discussion of the hydro-meteorological facts (i.e. rainfall-runoff process) as well as the geomorphological parameters (i.e. soil conditions and surface imperviousness) that are responsible for flooding occurrence and constitute the main inputs in the hydrological models is out of the scope of the present report. However, except for

[6] Ray, http://www.cfspress.com/carwater.htm

their contribution to the hazard itself, some of the aforementioned attributes, are also related to the vulnerability in terms of human and property exposure. For example, considering impervious surfaces, the urbanization is a factor that entails less infiltration capacity and thus, higher probability of runoff generation along with higher water depth (Maples and Tiefenbacher, 2009). But, urbanization means also more people and structures exposed. The following pages focus on the second perspective of equivocal concepts like urbanization to explore the human-related vulnerability factors. The main factors identified through the available literature are separated in three categories: a) Anthropogenic, b) life-cycle, and c) cognitive and mental factors.

a) Anthropogenic factors: In this study, the term "Anthropogenic" yields: (i) geospatial attributes (i.e. land use and catchment topography), (ii) structural attributes (i.e. build infrastructure) and (iii) risk prevention policy information (i.e. warning and emergency actions) that characterize the exposed area.

To begin with, the urban development (i.e. roads and infrastructure density) is a factor that entails higher probability of flooding along with higher water depth (Maples and Tiefenbacher, 2009). Changnon et al. (2000) states that 55%-85% of the peak flood flow increases in the Midwest river catchments for the period 1940-1990 were due to land-use changes and not due to the increase of the associated storm. Land-uses dominate the floodplain damages and complicate the hazard protection policies. In general, urbanization is supposed to impede evacuation and rescue processes within a flood event due to creating situations like traffic jams (FLOODsite, 2005). Urban development is explicitly associated with population growth and population density. Also, population growth is the cause of increased number of people in flood zones meaning more vulnerability (Montz and Gruntfest, 2002).

Regarding the drainage area, catchment time response is a factor that affects indirectly the human response to flash flooding. Characteristics such as the size and the slope of the catchment are related to the time response of the basins. Smaller is the basin faster is its reaction to the rainfall signal. In fact, in small catchments, the flood peak occurs only a short time after the excessive rainfall reducing the available time for anticipation and so, affecting people regardless their physical abilities to react. Though big drainage areas gain interest due to the assumption that a large amount of people is exposed, Ruin et al. (2008) showed that small catchments (< $20km^2$) are also responsible for the death of many people, especially middle age males who are mostly caught while driving. Steep slopes enforce flood swiftness reducing the available time for anticipation and/or preparedness, too.

Infrastructure collapses due to flood water are much considered by scientists in order to assess vulnerability of places to flooding (Kelman, 2002). The non-application of building codes is the most used vulnerability factor (Changnon et al., 2000). However, in case of small scale floods such as flash floods, infrastructure's ruin is not the major problem. But, the type of housing has been identified as an important characteristic for people's safety during a flood event (Jonkman, 2003). The fragility of buildings (i.e. poor constructions) has been discussed a lot in the literature to examine hazardous rescues or loss of life (FLOODsite, 2005). The number of floors or the existence of roof openings are both related to the people's ability to escape from flood waters (Priest et al., 2009). Furthermore the use of buildings determines the evacuation feasibility. For example, nursing homes are possibly difficult to be evacuated (Vinet et al., 2011). Also, schools or hospitals constitute "special needs" places from where population evacuation or removal is problematic (Cutter et al., 2000).

Flash floods outcomes also depend on the existence and efficiency of flood prevention systems that exist in the exposed society. Considering the sudden and violent nature of flash floods timely forecasting and warning is a challenge (Montz and Gruntfest, 2002). Three aspects related to warning are important to understand human vulnerability. Firstly, the existence of official and timely warnings determines the population ability to undertake protection actions (Staes et al., 1994). Secondly, the dissemination activity plays a significant role on informing people and also making them aware of the danger (Sharif et al., 2012). Thirdly, not only the warning itself but also how seriously people consider the warnings affects the lethal impacts during the flash flood (Vinet et al., 2011). On the other hand, the effectiveness of the emergency management (i.e. rescue operations) is of high importance to mitigate flash flood impacts. Last but not least, the existence of official flood prevention plans and especially measures to increase risk awareness is a factor that contributes positively to the prevention of losses (Duclos et al., 1991).

b) Life-Cycle factors: The term "Life-cycle" refers to: (i) the demographic (i.e. age, gender, e.c.t.) as well as the social (e.g. profession, housing ownership, family ties e.c.t) characteristics of individuals and households that define their position in the society.

The main factor of human (or social) vulnerability to flash floods and other natural hazards is the physical ability to move usually related to age (Cutter et al., 2003; McGuire et al., 2007; Vinet et al. 2011). It determines both the evacuation and the stability of people in running water (Jonkman et al., 2002). Hence, in most studies elderly (e.g. >65 yrs old) and/or children are supposed to be the most sensitive age groups (Blaikie et al., 1994; Tobin and Montz, 1997; Clark et al., 1998; King and Macgregor, 2000; Wu et al., 2002; Cutter et al,. 2003; Haki et al., 2004; Chakraborty et al., 2005; Azar and Rain, 2007; Muller et al., 2011). Vulnerability of these ages is also associated with the dependency that is a factor that explains the ability of people to act without the help of others or the capability to take initiatives in order to deal with flooding. But the inability to evacuate can be considered without being necessarily related to age. Indeed, some studies presented also young people (e.g. 20-60 yrs old) as a highly vulnerable group (Jonkman and Kelman, 2005). The long-term physical (i.e. health) condition is a decisive factor for all ages. Other demographics like the gender reveal additional flash flood vulnerability factors such as the risk-taking behavior. Some studies speak about "active" vulnerability that explains unnecessary human risk-taking behavior within a flash flood event (Ruin and Lutoff, 2004; Vinet et al., 2011). For example, in the 2010 flash flood in Var, two people died as they tried to move their car from a basement garage (Vinet et al., 2011). Since males are overrepresented in vehicle-related fatalities (French et al., 1983; Jonkman and Kelman, 2005; Haynes et al., 2009), this fact is usually attributed to the men's risk-taking behavior (Ryan and Hanes, 2010; Ashley and Ashley 2008; Vinet et al. 2011).

Independently from the demographic attributes other social circumstances shape vulnerability factors. The need for care-giving reduces the ability to undertake safety actions, too. For example, parents possibly disregard their safety in order to protect their kids. Especially single-parents are in difficult position being the only responsible for their children. They are often considered more vulnerable due to their lower income compared to the two-parent households (FLOODsite, 2005). This can also be related to other factors such as the access to resources useful for rescue or evacuation (e.g. car) (Enarson, 2007; Wilhelmi and Morss, 2012). Other important factors are the accessibility to external help or to important information during the event (Wilhelmi and Morss, 2012). These factors could be linked with the proximity of people to family members or neighbors and the linguistic ability to understand warnings. The contribution of neighbors and family members in rescue operations can be significant (Duclos et al., 1991). However, being in couple is not necessarily an attribute that eliminate threat for loss of life. Almost 51% of the people who died at home in the case of the storm Xynthia (2010) and the flash flood in Var (2010) were with someone else the time of the death (Vinet et al., 2011). The ability of a person to help another depends on other factors such as the physical disability or the health conditions.

Socio-economic attributes like people’s profession indicate additive factors such as the autonomy of individuals to re-schedule their daily routine to adapt to adverse/extreme conditions. For instance, a temporary employee who is afraid of losing his job might feel obliged to drive regardless of the weather conditions. On the other hand, a person who works at emergency services possibly ignores the need for self-protection due to the feeling of high responsibility. Thus, responsibility could be another specific vulnerability factor.

Finally, in the context of the “Life-cycle characteristics” that are examined here, the limited knowledge of the local area is recognized to be a possible factor of human susceptibility to flooding (FLOODsite 2005). Thus, population groups such as newcomers and migrants are considered to be at high risk (Blaikie et al. 1994). Also tourists belong to the same category since they do not have the required local knowledge nor experience that would help them consider the possible protective actions in case of emergency (Ruin, 2007).

c) Cognitive and mental factors: In the present study the cognitive factors are represented by two terms: (i) the risk perception and (ii) the mental representation that are related to conscious or unconscious perspectives of individuals.

The risk perception encompasses the viewpoints of individuals about how much they are exposed to risk and how to deal with flash flooding. Risk awareness and education are important factors for preparedness and adaptation ability. Since evacuation and rescue are the dominant safety actions during a flood event (Lindell and Perry, 1991), the level of education about these processes is a crucial factor for people protection. Many elderly people die as a result of not knowing how to behave during flooding (Caroll et al., 2009). Haynes at al. (2009) support that evacuation is not always the safest option especially when it is associated with late warnings and very short available time for protection. Therefore, enhancement of population’s awareness against the life-threatening power of floods is very important in order to help people to take the appropriate decision at the time of flooding (Ashley and Ashley, 2008). On the other hand, despite the flood risk awareness, in some cases local residents ignore the safety advice and take risks more or less consciously. Thus, not only tourists or foreigners are sensitive due to the lack of local area knowledge or the limited linguistic skills, but also permanent population that decides to not taking into account the received warnings (Vinet et al., 2011). This behavior could be linked to the lack of trust in the official warnings or to the individual estimation of flood risk that is one of the main factors that exacerbate human vulnerability (Montz and Gruntfest, 2002). At a certain level, the estimation of risk is determined by the personal experience with past flood events. The past-event experience could lead to various behaviors in time of flooding. For example, people can be shocked and be unable to react since past memories block their feelings during the flood. On the contrary, some people could expect that flood forcing is similar to their past knowledge and so they feel secure ignoring the forthcoming danger.

The mental representation is hazard-independent concept and explains how people feel about the place that they are or the activity that they are doing during their daily-life routine when a hazardous event occurs. Thus, the main factor related to this concept is the attachment of people to a specific place. For example, old people or people that own a house can be less willing to abandon their belongings when they are at home during flash flooding. In some cases, people died after attempting to rescue some of their belongings (Jonkman and Kelman, 2005). It means that not only the ability but also the willingness to evacuate is equally important (King and MacGregor, 2000). In the literature, most of the flood fatalities in U.S (Staes et al., 1994; Ashley and Ashley, 2008; Maples and Tienfenbacher, 2009; Sharif et al., 2012), Australia (Coates, 1999; FitzGerald et al., 2010) and Europe (Jonkman and Kelman, 2005; Diakakis and Deligiannakis, 2013) are vehicle-related. But what make people move through the flood water? Staes et al. (1994) found that "being in a vehicle during the 1992 flash flood in Puerto Rico for reasons other than to evacuate further increased the risk of mortality". It can be the sense of an obligatory activity that makes people to try to move during bad weather conditions together with feelings such as confidence in the safety of their automobile or the driver's capabilities due to personal past experience in driving under flood conditions (Maples and Tienfenbacher, 2009). Similarly, familiarity with the roadway which can be assumed for routes close to the home location or between home and work place, is an important factor of overconfidence of drivers (Ruin et al. 2007; Maples and Tienfenbacher, 2009).

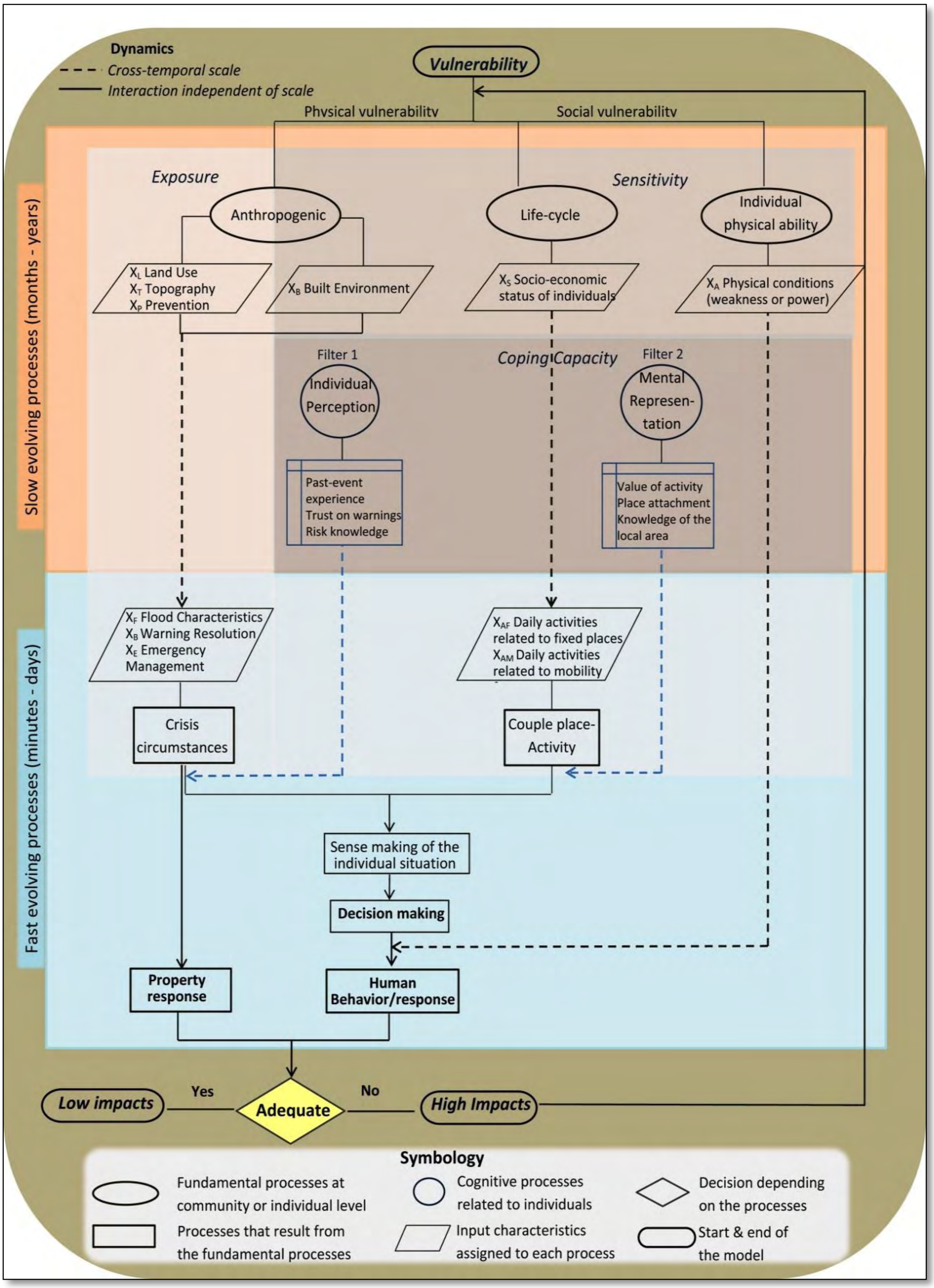
3.2. Conceptual model for the assessment of vulnerability to flash flood

The goal of the developed conceptual model (Figure 5) is to present the set of processes and the related dynamics that have to be considered in the integrated vulnerability analysis in order to predict the level of impacts that could be expected with the occurrence of a flash flood event.

3.2.1. Structure of the model

The construction of the conceptual model in this study is guided by the need to contextualize the vulnerability factors discussed in the previous paragraph of the present report into the temporal scale of the flash flood phenomenon. For this reason, the basic structure (Figure 3) consists of: (i) discrimination of the processes in terms of their rate of evolution in time (light orange and light blue rectangles in the background) and (ii) the interactions from one temporal scale to the other (dashed lines). "Slow evolving" is a term used to explain processes that develop over months to years and contribute to shape the pre-existing conditions of the flooding event (see anthropogenic, life-cycle and cognitive factors in 3.1.2).

On the other hand, the "fast evolving processes" develop over duration ranging from minutes to a few days and therefore can enter in resonance with the dynamic flooding phenomena. In other words, in order to understand the potential impacts we focus on the coupled physical and social circumstances that interplay during the event (i.e. fast evolving processes) and their relationship with the slow evolving processes that constitute the aforementioned vulnerability factors. The processes are also positioned on the model according to the underlying vulnerability determinant (i.e. exposure, sensitivity and coping capacity) that they express (very light, light and dark grey rectangles, respectively) based on the proposed flash flood vulnerability



framework described in section 2.1.2.

Figure 3. Flash flood Conceptual Vulnerability model.

3.2.2. Model concepts and the embedded functions

The main contribution of the present model compared to previous vulnerability models is that it not only presents the main long-term factors that are responsible for the human losses (static vulnerability) but it seeks to answer the challenging question of what really is happening in the short duration of flash flooding (dynamic vulnerability). But to answer this question, individual behavioral concepts have to be incorporated in the vulnerability assessment model.

In a broad sense, the behaviour of people during the flash flood is determined by the intersection of the flash flood event (expressed as “Crisis circumstances” here) with the daily schedule of individuals (expressed as “Couple place-activity” here). Crisis circumstances refer to the flooding itself (e.g. water depth) as well as other attributes such as the spatial-temporal resolution (i.e. spatial extend and the corresponding lead time) and the timing (i.e. day or night) of the official warnings that shape the situation of a specific flash flood event. These characteristics are the output of the flash flood hydrological forecast models (not discussed here) and the long-term anthropogenic factors (i.e. the decisions taken on the national or community level concerning the occupancy of land and the hazard prevention policy). For example, a “crisis circumstance” can be the occurrence of high depth of runoff on the road network due to the intense urbanization (i.e. limited ground infiltration) in the area of interest. The Crisis Circumstances define the Property response, meaning the way that the built environment reacts due to its contact with the flooding conditions (e.g. the collapse of an old and/or pour-material building when the fast moving water impinges on it).

The Couple place-activity concept represents the daily routine of people including where they are (e.g. inside a building, on the road e.c.t.) and what they are doing (e.g. working, getting rest e.c.t.) at the different times of the 24h day. This concept evolves out of time geography (or time-space geography) science that describes the sequential path (called also life path) of personal human events (with time and place as dimensions) that marks the history of a person (Gamow, 1970) within a situational context (Hägerstrand, 1970). Hägerstrand (1970) stated that "life paths become captured within a net of constraints, some of which are imposed by physiological and physical necessities and some imposed by private and common decisions." In natural hazards science this means that depending on contingent conditions (e.g. rush hours when there are errands to run and children to pick up and lots of other cars on the road, or working hours when people feel they must be at work regardless of the conditions) perception of environmental cues and warning messages may be hindered (Ruin, 2007, 2010). Likewise, the nature and dynamics of the individuals’ reactions will differ according to the location and activity they were performing when they felt the need for action, and their capability to connect with their relatives or to have social interactions allowing a group response (Gruntfest 1977; Mileti 1995; Drabek 2000; Lindell and Perry 2004, Ruin et al., 2014).

Those contextual factors results from all the pre-mentioned Life-cycle characteristics. For example, a young man who is an employee at a company uses to be at work during the morning hours whereas an old retired man has more chance to be at home at that time period. Depending on where people are and what activity they perform at the time of the flooding (interaction with the Crisis circumstances) people can get a different idea of the actual event.

At this point it has to be noticed that the human behavior in case of a life-threatening event is not a simply defined process related directly to the crisis and the couple place-activity processes. Intermediate cognitive processes play a fundamental role in the choice of behavior (Figure 4). The cognitive processes described in paragraph 3.2.1 (Filter 1 and Filter 2 in Figure 3) interact with the Crisis Circumstances and the Couple place-activity processes and shape the individuals' final sense of their situation. For example, a person who has the experience of flooding situations might perceive the danger differently than someone without flooding experience. These interactions are very important because they are responsible for the decisions taken by the people during the flood event. However, the final reaction of people during a hypothetical flash flood is not only determined by the decision that they have made according to all the pre-mentioned functions but also by the real physical ability that they have to implement their decisions.

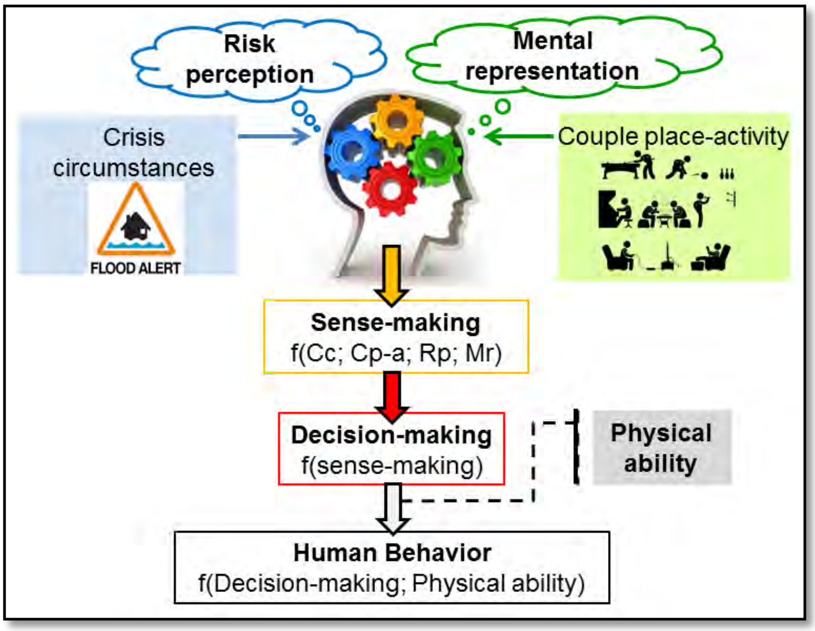


Figure 4. Human behavior as a function of cognitive processes and contingent circumstances.

4. FLASH FLOOD VULNERABILITY INDICATORS

4.1. Vulnerability measurement using indicators

In general, vulnerability assessment and quantification is not as advanced as the hazard mapping and quantification. This is probably due to the difficulty to quantify some aspects of vulnerability concerning people's behavior and susceptibility discussed in the previous section of this study. Indicators are, among others, useful tools for the quantification of relevant individual, households or neighborhoods aspects that explain the level of vulnerability and measure risk (Birkman, 2006). In the literature regarding natural hazards indicators are divided in economic, social and environmental or ecological (Kumpulainen, 2006) or more broadly in biophysical and social (Cutter et al., 2000) reflecting the respective dimensions of vulnerability (Birkman, 2006). Indicators focusing on human characteristics can also be categorized according to the social scale that they refer to (i.e. individual or household level, administrative community level, country level e.c.t) independently from the hazard scale (Birkman, 2006). The use of indicators allows the creation of a common (dimensionless) measure of vulnerability. Also, indicators enable comparison of vulnerability among different places or among different times in a specific area of interest.

4.1.1. Review of natural hazards studies using indicators

In recent years most of the studies used indicators in order to evaluate risk and consequently vulnerability to different natural hazards by creating indices at a national (UNDP, 2004; Cardona, 2005) or sub-national (Dilley et al., 2005) level for international or global-oriented projects. At this coarse scale indices that are composed by several indicators use only one numeric value to describe an entire country ignoring the possible variability within that country. Some examples are the Social Vulnerability Index (Cutter et al., 2003); the Disaster Risk Index (UNDP, 2004) and the Prevalent Vulnerability Index (PVI) (Cardona, 2005). A disadvantage of the aforementioned approaches is that they view vulnerability as an intrinsic component of risk without focusing on the specialties that are fostered depending on the hazard type. The scarcity of a hazard-specific context makes the large-scale hazards with high amount of fatalities to gain prominence in the previous studies. Contrariwise, small-scale (e.g. flash floods) or low-frequency (e.g. tsunamis) hazards are not very well represented. In the frame of the socially oriented studies where vulnerability is considered as an internal property of the society, Cutter et al. (2009) highlights some broad indicators that appear frequently in the literature irrespectively of the proxy variables that are selected to represent them. The socioeconomic status (wealth or poverty); the age; the special needs populations; the gender; and the race and/or the ethnicity are some of the most commonly used characteristics (Tierney et al., 2001; Heinz Center, 2002; Wisner et al., 2003; National Research Council, 2006; Bates and Swan, 2007). In particular, Cutter et al. (2003) with the development of the Social Vulnerability Index (SoVI) for the county level proposed eleven social vulnerability indicators that have been the base of several other analyses in the literature (Rygel et al., 2006; Azar, D. and Rain, D., 2007; Frazier et al., 2008). According to our critical analysis, the drawback in the process proposed by Cutter et al. (2003) is that social variables are over-represented. Although the integration of physical and social vulnerability is recommended, the concept of exposure that composes physical vulnerability is only represented by the relative frequency (i.e. probability of occurrence) of each hazard underestimating the intensity and the spatio-temporal configuration of the natural event.

Similar efforts have been done in assessing vulnerability to different natural hazards at more local scale such as community level. Unfortunately, they still provide macro analysis not able to capture the local circumstances (Chakrabatory et al., 2005; Kienberger, 2007). The main shortcoming is that usually population characteristics (e.g. demographic information) are used as constants that provide a certain level of vulnerability. The dynamic nature of the physical or anthropogenic attributes is excluded from the analysis. This means that concepts such as human behaviours and coping capacities that are characterized by faster temporal evolution are not considered at all. Despite all the aforementioned limitations, the previous studies could still provide with some useful ideas for the selection of the indicators in the present study.

4.1.2. Review of flood hazard studies using indicators

Concerning studies on hydrological hazards such as floods, many scientists used GIS-based approaches to assess and map flood risk (Meyer et al., 2009) or flood vulnerability (Linde et al., 2011) using indicators. Müller et al. (2011) develop a case-specific set of indicators to empirically assess the flood vulnerability of the city of Santiago de Chile to urban flooding. Though this study is restricted to the specific case study, the selection of physical and social indicators based on experts' as well as local residents' perspective is interesting. Other flood vulnerability studies focused on the social aspect of vulnerability based on the use of census data (Fekete, 2009). Wu et al. (2002) reused social attributes (e.g. age, gender, race, income and housing) proposed by Cutter et al. (2000) and combined them with physical data (e.g. drainage area slope, water depth, land uses) in order to produce a holistic map of vulnerability to both riverine flooding and coastal storm surges in Cape May County (USA). This contribution presents an assessment of overall vulnerability to flood hazard but it is still captive in the static consideration of the social susceptibility and the coarse spatial scale that sidetracks local variability of vulnerability. Azar and Rain (2007) emphasizes the fallacy of the demographic analysis presented by Cutter (1996) and Cutter et al. (2000; 2003) to represent the diversity of vulnerability at the scale of a neighborhood. To go towards this direction Azar and Rain (2007) perform a rasterization of social vulnerability layer that is in agreement with the physical layer resolution in GIS. Of course, this approach is simplified. The incorporation of people movement and activities during the day in vulnerability assessments requires careful consideration. Due to the difficulty to capture the temporal variability of the human activity, many studies confine the flood vulnerability analysis performing exposure quantification based mainly on land-use indicators (Camarasa Belmonte et al. 2010; Calianno et al., 2013).

It is apparent that while there is a lot of research on understanding flood impacts and the underlying vulnerability causes (see for details paragraph 3.1), the establishment of specific vulnerability metrics is much rarer. Especially, little work on vulnerability mapping has been cited in flash flooding frame (Camarasa Belmonte et al., 2010; Wilhelmi and Morss, 2012; Calianno et al., 2013). So far, there is no study that offers a comprehensive set of relevant variables that could be used for the mapping of both physical and anthropogenic elements in case of flash floods. Barroca et al. (2006) developed a tool for the selection of indicators concerning vulnerability to urban flooding. That work that is more focused on flood prevention perspective is valuable to facilitate a set of indicators in the crudest sense but it is far from providing a list of indicators for the particular conditions of flash flooding. To address the lack of literature on measurement of vulnerability to flash floods, the present work efforts to recognize the most important vulnerability indicators used in natural hazards studies to see their applicability in the context of flash flood.

4.2. Selection of flash flood-relevant indicators

In the present study, the selection of indicators and proxy variables (Table 2) is based on a critical synthesis of the pre-mentioned literature on flood casualties as well as the available literature on vulnerability indicators to floods and natural hazards in general. Through the literature review, it is realized that the same indicators can have different meanings depending on the type of hazard and the exposed society. For example, Indicators determination depends on the target and the scale of analysis. For instance, income is a prevalent indicator in country level studies assessing vulnerability to different hazards (Blaikie et al. 1994; Tobin and Montz 1997; Yohe and Tol, 2002; Cutter et al., 2003; Birkman, 2006). When the economic disruption caused by different natural hazards is considered high income means higher value of endangered infrastructure and contributes negatively to vulnerability (Kumpulainen, 2006). On the other hand, low income is supposed to be the critical variable to measure the incapacity of people and countries to access resources and cope with a catastrophe (Clark et al. 1998; Cutter et al., 2003; Kumpulainen, 2006). This is evident mainly in the low-income (i.e. developing) countries (Doocy et al., 2013). Nevertheless, the variable "income" is not much representative of flash flood casualties especially for the developed countries that are considered in the present study. During such a short and violent event the economic condition of people cannot prevent their harm. Thus, the selection of the most suitable vulnerability variables is a difficult task and has always to meet the purpose of the analysis. In addition to that, data availability is an important constraint for selecting indicators and constructing indices. The present study seeks to provide a complete set of indicators free of data restrictions (not data-driven) but still considering the applicability of the corresponding proxies.

4.2.1. Set of variables relevant for flash flood vulnerability

The proposed indicators are listed in Table 2 associated with their relevance according to the vulnerability factors that they represent. The indicators are organized according to their relation with the input characteristics included in the conceptual model presented in the previous section (Figure 3). Rather than separating them by their physical or social nature the author presents the indicators in a comprehensive framework considering the underlying interrelation between the built and the human environment. Table 5 is also inclusive of a list of possible proxy variables that could be assigned to each indicator in agreement with the existing literature or the author's perception. For example, land use classification presented here is based on the Calianno et al.'s (2013) analysis of flash flood impacts in U.S whereas the building characteristics are described based on Kappes et al.'s (2012) multi-hazards analysis. It has to be mentioned that they do not constitute a definitive choice but they can be adapted or modified depending on the application to a specific case study. Thus, these proxies are subject for revision and reclassification in the future. The proposal of possible proxies allows the statement of a main hypothesis that represents the position of the author about how each indicator increases or decreases the vulnerability to flash flooding.

Code No	Indicator	Relevance	Proxy Variable	Main Hypothesis
Land Use				
1	Land cover	Indicates the nature of the potentially exposed elements.	Natural vegetation Cropland Developed-open space Developed-low intensity Developed-high intensity	Highly-developed areas cause more flooding and pose more people and property at risk.
2	Population density (inh/km^2)	Determines the amount of elements at risk.	Very low (≤4) Low (4-70) High (70-500) Very high (>500)	Places with high density reveal high exposure
3	Proximity to permanent/non-permanent river/streams (m)	Indicates the likelihood of flood occurrence and the level of exposure.	Far away/fourth row (>250) Away/third row (100-250) Close/second row (50-100) Close/first row (0-50)	Areas close to streams or rivers are more exposed.
Topography				
4	Catchment size (km^2)	Determines the catchment time response/Affects the available anticipation time.	Big (100-1000) Small (20-100) Very small (≤20)	Small catchments limit the time for anticipation and increase the risk for people in their vehicle or performing activities in the open air.
5	Catchment upslope (^{o})	Affects the swiftness of the hydrological response and the destructive power of water.	Very low (≤0.2) Low (0.2-0.6) Intense (≥0.6)	Steep slopes increase the velocity of the flood water, its capacity to float debris and to create damage and loss of life.
Long-term Prevention				
6	Flood zoning	Represents the level of flood plain management regulation related to the location.	Use levels applied in each country Non existent	Lack of flood zoning means the risk might stay unknown to inhabitants who are therefore enable to be prepared for it.
7	Flood defence	Represents the risk associated with the likelihood of failure of dams/levees/ Affects people perception of security.	Non existent Existence	Flood defence's failure can cause fast submersion. Living behind flood defences generally gives the inhabitants a false sentiment of security.
8	Warning verification	Influence the trust that inhabitants may feel about official warnings issued from their local offices.	Good performance of the average forecast (e.g. 5 yrs forecasts) Bad performance of the average forecast	Low success of past forecasts means limited trust of people on the FF warnings.
9	Warning	Determines the	More than 2 languages Official + Secondary	Warning available

	Language	efficacy of warning dissemination and comprehension.	language of the region Only the official language of the region	only in one language means limited comprehension by immigrants or foreigners with different native language.
10	Alternative communication means	Determines the redundancy of the communication network needed for information.	Three medias Two medias One media	The less communication media are available the less information is disseminated to people during the crisis.
11	Mitigation measures	Indicates the existence of measures to increase flood risk awareness and preparedness among the residents.	Existence of persistent mitigation measures Existence of punctual mitigation measures Non-existence of mitigation measures	Communities that have not implemented long-term risk mitigation strategies might experience less efficient warning/crisis response.
12	Rescue services accessibility	Shows the rescue capability.	Within short (e.g. 15mn) travel time Within long travel time	Rescue services in a long distance from the flooded area are less able to respond in a timely manner.
		Built environment-Buildings		
13	Building age (yr)	Represents the building condition and the safety level for people inside.	Very New (≤10) New (10-20) Old (20-50) Very old (≥50)	Old buildings might be less able to withstand the power of flooding water.
14	Building material	Shows the quality of the building material and the suitability for sheltering.	Concrete Metal Mixed Tranditional brick wall Wood	Light-material structures (e.g. wood) are less resistant to flood water with a potential risk of collapse.
15	Mobile homes or caravans	Shows the quality of the houses and the suitability for sheltering.	Number below the average Number above the average	Mobile homes are less resistant to flood water with a potential risk of collapse.
16	Building number of storeys	Determines the likelihood of flooding and the sheltering availability.	More than two Two stories One story	One-storey buildings do not offer adequate sheltering.
17	Presence of basement		No living basement Living/sleeping basement	Basements are the first to be flooded. Basement used as living/sleeping space could increase the cost of damage and the loss of life risk during the night.
18	Building floor height (m)	Determines the likelihood of flooding on	Low (<2.5) Normal (2.5-3) High (>3)	Low floor heights are more easily flooded/Inadequate

		building.		sheltering.
19	Building windows	Represent the fragility toward flood waters.	Unprotected	Unprotected windows means property and people can be more easily damaged.
			Protected	
20	Building roof openings	Determine the population ability to escape.	Existence of openings	No roof openings mean inability to be rescued.
			No existence	
21	Special Needs buildings	Indicates the evacuation ability of specific population groups.	Youth centres	Special needs population has limited ability to evacuate or be easily rescued.
			Schools	
			Prisons	
			Hospitals/clinics	
Built environment-Road networks				
22	Road network density (r/km^2)	Indicates risk associated with travelling activities.	Below the average in the exposed area	Dense network means more chance of damage to road infrastructure and risk of car-related accidents due to runoff.
			Above the average	
23	Road network age (yr)	Shows the level of road quality.	Very New (≤10)	Old roads tend to collapse more easily leading to unsafe conditions for drivers.
			New (10-20)	
			Old (20-50)	
			Very old (≥50)	
24	Bridges density (b/km^2)	Indicates the level of exposure for road users.	Below the average in the exposed area	High number of bridges means higher probability for bridge failure and population harm.
			Above the average	
25	Low-water crossings density (lw/km^2)		Below the average in the exposed area	High number of low water crossings increases the possibility of vehicle-related accidents.
			Above the average	
26	Road network redudancy	Represents the accessibility of terrestrial rescue patrols and the possibility of escaping for drivers confronted with flooded roads.	Existence of alternative routes leading to one destination	Absence of adequate alternative routes means people's inability to receive external help or escape.
			No existence of alternative routes leading to one destination	
Runoff characteristics				
27	Flood water depth (m)	Defines the level of risk for property and people.	Low (≤0.1)	High water depth is responsible for more damages and drowning.
			Medium (0.1-0.3)	
			High (>0.3)	
28	Flood water movement		Standing	High speed waters sweep away property and people.
			Moving	
			Fast moving	
29	Flood/rainfall return period (yr)	Represents the severity of the event.	Below the threshold return period	The most severe impacts are associated with the rarer events (longer return period).
			Above the threshold	
Warning Response				
30	Warning	Represents the	Catchment	Less localized is the

	Polygon size	spatial-temporal precision of the warning/Affect people's risk perception and personalization.	Municipality	warning, less seriously it is considered by people (risk underestimation).
			County	
31	Warning lead time		Short	
			Long	
			Night (Sleeping hours)	
32	Past-flooding Experience	Determines the risk awareness and the personal culture of risk./Depends on the combination of the length of residence and the frequency of flooding in an area.	Experience	No experience lead people to underestimate the flood risk.
			No experience during the residence length	
			Within long travel time	
Individual Socio-economic status				
33	People Age (yr)	Indicates the physical condition and the dependency to others. It is also related to the willingness to move.	Young-Active people (20-65)	Old people are less informed or disable to evacuate their home especially during night. Young people are in danger while travelling due to their reliance on the daily routine during the day.
			Children (≤8)	
			Elderly (≥75)	
34	Gender	Represents the risk-taking behaviour. Affects the mobility decisions during flooding.	Females	Male drivers are more prone to risk-taking behaviour.
			Males	
35	Family status	Indicates the need for care-giving and the responsibility to protect others.	Single	Single-parents are supposed to have less access to evacuation means (e.g. car). Parents ignore their self-protection to protect their children.
			Couple	
			Family	
			Family-Single parents	
36	Type of employment	Represents the level of economic pressure and autonomy to re-schedule the daily work-related activity.	Unemployed	Temporary employees may be less flexible to re-schedule their work–related activity because they might feel afraid of losing their job. Lack of flexibility could influence their ability to switch from daily routine to protective action.
			Employers	
			Permanent employees	
			Temporary employees	
37	Professional expertise		Non expertise-positioned	Non-experts are more prone to lose their job and postpone their
			High (leading)-positioned	

				self-protection.
38	Hazard-related occupation	Determines the level of exposure to flooding related to professional responsibility.	Not event-related employees	Emergency employers are the first responders taking risk in rescuing people.
			Emergency rescuers	
39	Housing ownership	Represents the economical ability for self-protection and/or the place attachment.	Owners	Homeless have limited access to shelter (specially unofficial ones). Owners feel attached to their place and may be more reluctant to evacuation measures.
			Renters	
			Homeless	
40	Language	Defines the ability to communicate and receive information.	Official (same as warnings)	Foreign speakers are linguistically isolated and may be less aware of the potential danger
			Foreign	
41	Vehicle available	Indicates availability of a vehicle for emergency and evacuation planning.	Yes	Households with no access to vehicle have limited ability to evacuate and move away from flooding.
			No	
42	Family ties	Indicates the geographic proximity to the family members and the possibility of receiving help during the event.	Close to family	People living far from their family have less chance to receive emergency help for evacuation/protection activities.
			Far from the family	
43	Proximity of Neighbours	Indicates the level of geographic isolation and the possibility of receiving help from others during the event.	Close to neighbours	Isolated people have less chance to be informed and/or to receive emergency help for evacuation/protection activities.
			Far from neighbours	
44	Length of residence in the municipality (yr)	Defines the level of familiarity with the area and the relationship with the local inhabitants.	High (≥5)	People living for a short period of time in a place have limited knowledge of the area and less chance to receive help during flood.
			Medium (2-5)	
			Low (≤1)	
			Medium (2-5)	
			Low (≤1)	
Physical (health) conditions				
45	Long-term health	Determines the physical ability to escape from unsafe conditions.	Healthy (without permanent disease)	Long-term sick and especially disabled people are mostly in danger due to their weakness to move and/or their dependence on permanent medical support.
			Long-term sick	
			Disabled/amputee	

Daily activities				
46	Flexibility of economic/livelihood activity	Shows the ability of economic activities to adapt their daily functioning to emergency situations.	High level of flexibility	Economic sectors that rely on a just-in-time basis may have less capacity to adapt to environmental perturbations.
			Medium level of flexibility	
			Low level of flexibility	
47	Means of transportation to work	Indicates the reliance of individuals on personal or public means of transportation	Public transportation means	People who use personal vehicle are more prone than others to suffer weather/flood-related car accidents.
			Personal vehicle	
48	Trip to work frequency (times/day)	Represents the level of familiarity of people with the route and affects the estimation of risk.	Low (<1)	People who use a route frequently feel more familiar with it and they underestimate the danger of travelling across flood waters.
			High (>2)	

Table 2. Indicators and proxies relevant for the assessment of vulnerability to flash flood.

4.2.2. Variability of flash flood vulnerability indicators

Vulnerability is everywhere and is formed at any time. Variability does not mean that there are places or times without vulnerability. But it is the interrelationship between the variables corresponding to the slow-evolving processes and the ones related to the fast-evolving processes (see the flash flood conceptual vulnerability model in paragraph 3.2) that creates a higher or lower level of vulnerability for each situation.

The dynamic nature of vulnerability could be expressed by using different set of the aforementioned indicators depending on the location and timing at which flooding occurs. In addition to that, sometimes the use of a specific indicator in a different way (i.e. different meaning of its proxies) is also recommended to describe the local vulnerability in time and space. This means that different importance (i.e. weighting) could be assigned to each vulnerability variable (i.e. indicator or proxy) to represent the difference of vulnerability depending on the characteristics of the specific events (i.e. location, timing and dynamics). There are, however, indicators that can be included in the vulnerability analysis with the same weight independently of the characteristics of the specific events. It means that these indicators have the same relevance if the flooding occurs during day or night (e.g. Land use, Topography, Long-term Prevention in Table 2). These indicators can also be applied by considering their proxies uniquely (i.e. with the same meaning). For example, highly developed areas are supposed to increase vulnerability (i.e. receive the highest weight) independently of the timing and the location of the flood.

The variability of vulnerability is built based on assumptions about a) the variability related to the timing of flood occurrence; b) variability depending on the flash flood dynamics and c) the variability in terms of exposure, sensitivity and coping capacity:

a) The timing of the flood corresponds to the level of lighting. Night related to darkness conditions (i.e. limited visibility), is an inhibitory factor for the performance of rescue operations and safe driving (Maples and Tiefenbacher, 2009). Also night is linked with the rest hours. Thus, night-time exacerbates the surprising character of flash and lessens the capacity of people to make sense of the situation and to respond effectively (Mooney et al., 1983). This is because warning dissemination and perception of environmental cues are hindered during the night (i.e. less people have access to the warning messages because of sleeping). On the other hand, day-time (i.e. lighting conditions) contributes positively to the reduction of the related vulnerability by increasing the coping capacity of people.

b) The space-time scale of flooding determines the dynamic nature of the phenomenon. Space is related to the catchment size. As mentioned before, small catchments (a few square kilometres) are characterized by short time response and limit the anticipation time of people. Such a dynamic and fast event has more chance to trap people in their vehicle or during activities in the open air especially during rush hours. Thus, variables related to the road network are of greater importance in case of small catchments. Open-air locations such as the road networks are where most of the fatal accidents happen in flash flood conditions (Sharif et al., 2012; Diakakis and Deligiannakis, 2013). Flash floods (< 1 h response) can have less effects in terms of building collapse in comparison to the structural ruin resulting from a fast but not so flashy event (1h<t<6h). Although vulnerability is everywhere, sometimes people who stay inside an adequate shelter, are at lower risk than when traveling on the road (Ruin et al., 2008).

On the other hand, in bigger drainage areas (hundreds to thousand km^2) fast flooding presents similar characteristics with river flooding. This means that the energy of river dominates the flood severity, so building attributes are also very important revealing the potential risk for collapse. Thus, there are indicators that have different relevance depending on the type of flood dynamics (e.g. Built-environment-Buildings and Built environment-Road networks in Table 2). For example, the indicator “building material” would have a higher weight in case of larger catchments especially when residential or industrial areas are considered (see place types in Table 3). These indicators have unambiguous definition of their proxies. This means that for example, old buildings or road networks are always more dangerous than the newer ones.

c) The variability of exposure depends on the different occupancy of the same space as a function of time during the 24h of the day (“quantity” of elements at risk). It means that for example, more people are at work (i.e. Industrial/commercial area) during the working hours; on the road (i.e. Road network) during the rush hours; at home (i.e. Residential area) during the rest hours; and at the leisure places (i.e. Recreation area) during the holidays/weekends (Camarasa Belmonte et al., 2010).

The variability of sensitivity and coping capacity depends on the different contribution of the individual’s characteristics (e.g. Individual socio-economic status and/or Daily activities in Table 2) on the definition of a crisis situation. It means for example, that class of workers who are employed by time-sensitive businesses may not feel free to adapt their scheduled activities in case of bad weather conditions. As they might be less able to turn around or cancel their work-related journey, they could be considered a sensitive population when flooding conditions happen around commuting hours (Ruin, 2010). In that case the relevance of the indicators and their proxies’ definition varies according to where and when flash flood occurs (Table 3). In Table 3 hypothetical situations that combine the type of the place people usually occupy at specific time periods are defined.

Table 3 can be viewed in three ways. In some cases the place is the main determinant whereas the time is an underlying vulnerability factor. For example, the use of the housing ownership variable is mostly relevant for the evaluation of the vulnerability of people when they are located in residential areas. In fact, owners are supposed to be more vulnerable when at home due to their attachment to their belongings and their unwillingness to evacuate. On the other hand, workers who are also car-owners will be mostly vulnerable on the road during commuting hours. Both of them, however, have different level of vulnerability depending on the timing, with the night conditions to exacerbate their vulnerability.

The second way to look at Table 3 is to identify how the available proxies contribute positively or negatively to the vulnerability based primarily on the time period and secondary on the location factor. For example, the indicator special needs building have different importance depending mainly on the difference between day-active hours and night-rest hours. This means that although special needs building are generally highly vulnerable, some, like schools, are mostly vulnerable during daytime and outside holiday’s periods (when not used as emergency shelter).

A third way to understand the “place-timing driven indicators” is based on examining the interactions of time period and place type simultaneously. For example, age is one of the most important characteristics of individuals in several cases (e.g. day/working hours-Educational area, day/working hours-Industrial areas, day/rush hours-Road network, night/rest hours-Residential area, holidays-Recreation area e.c.t). However, the importance of its proxies presents a high level of variability. For example, elderly people are supposed to be at high risk being isolated at home during night but they are not representative of vulnerability during day/working hours at schools.

Time period / Pace type	Day/Light		Night/Darkness	Holidays
	Working hours	Rush hours	Rest hours	
Recreational				I_{33} People age (young) I_{40} Language (foreign)
Road Network	I_{38} Hazard-related occupation (emergency rescuers)	I_{33} People age (young) I_{41} Vehicle available (Yes) I_{34} Gender (Males) I_{35} Family status (Family) I_{36} Type of employment (Temporary) I_{47} Means of transportation to work (Personal car)		
Industrial/ Commercial	I_{33} People age (young) I_{37} Professional expertise (Non expertized)		I_{38} Hazard-related occupation (emergency rescuers)	
Educational/ Sanitary	I_{33} People age (Children) I_{21} Special Needs buildings (Schools)		I_{21} Special Needs buildings (Hospitals)	
Residential			I_{33} People age (Elderly) I_{40} Language (foreign) I_{39} Housing ownership (Owner) I_{41} Vehicle available (No) I_{35} Family status (Single-parent) I_{42} Family ties (Far) I_{43} Proximity to neighbours (Far	

Table 3. Vulnerability indicators' variability depending on the flash flood location and timing.

4.3. Computational model for the assessment of vulnerability to Flash Floods

The evaluation of the ability of the indicators proposed in the previous section (Table 2) to explain vulnerability to flash floods, requires firstly the existence of a vulnerability assessment computational method and secondly, the existence of an adequate impact dataset to be compared with the results of the vulnerability assessment. The successfulness of both the conceptual and the computational model would be validated if the recorded impacts of past flash floods in specific case studies are in agreement with the measured level of vulnerability (i.e. high impacts-high vulnerability; low impacts-low vulnerability). This section introduces an indicator-based model (Figure 4) for the assessment of vulnerability which has to be validated using real impacts observations in the future.

4.3.1. Indicators and data collection for the vulnerability assessment

A different amount of the proposed indicators listed in Table 2 can be used depending on the purpose of the analysis and the data availability in each case study. Since the present work seeks to provide a general framework of indicators, Table 2 includes variables that already exist in official datasets like census data or variables that can serve as data after a simple processing. In case that some variables are not easily readily (e.g. family ties), data have to be collected through site-specific surveys suitable to represent the specific cultures and certain structural requirements (e.g. building codes) of the study area. Table 4 provides a coarse discrimination of indicators that include easily defined proxy variables (i.e. variables commonly used in the literature) and proxies that can usually be obtained indirectly by other models or a relatively simple processing.

FROM OFFICIAL DATASETS		
I_1 Land cover	I_{15} Mobile homes or caravans	I_{38} Hazard-related occupation
I_2 Population density	I_{16} Building number of storeys	I_{39} Housing ownership
I_6 Flood zoning	I_{21} Special needs buildings	I_{40} Language
I_7 Flood defence	I_{23} Road network age	I_{41} Vehicle available
I_9 Warning language	I_{33} People age	I_{44} Length of residence in the municipality
I_{10} Alternative communication means	I_{34} Gender	I_{45} Long-term health
I_{11} Mitigation measures	I_{35} Family status	I_{46} Flexibility of economic/livelihood activity
I_{13} Building age	I_{36}Type of employment	
I_{14} Building material	I_{37} Professional expertise	
FROM OTHER MODELS/ PROCESSING		
I_3 Proximity to permanent/non-permanent river/stream	I_{20} Building roof openings	I_{31} Warning lead time
I_4 Catchment size	I_{24} Bridges density	I_{32} Past flooding experience
I_5 Catchment upsplope	I_{25} Low-water crossings density	I_{42} Family ties
I_8 Warning verification	I_{26} Road network redudancy	I_{43} Proximity of neighbours
I_{12} Rescue services accessibility	I_{27} Flood water depth	I_{47} Means of transportation to work
I_{17} Presence of basement	I_{28} Flood water movement	I_{48} Trip to work frequency
I_{18} Building floor height	I_{29} Flood/rainfall return period	
I_{19} Building windows	I_{30} Warning polygon size	

Table 4. Categorization of vulnerability indicators according to the accessibility on the related data.

4.3.2. Indicators and proxies weighting for the vulnerability assessment

The computational model proposed here (Figure 4) is based on the performance of two types of weighting the variables (i.e. indicators and proxies) that are included in the analysis at a specific case study. The first weighting gives an importance to each proxy variable based on the place and timing analysis presented in paragraph 4.2.2. At this step, the importance of some proxy variables have to be considered with the same meaning (i.e. constant weight). This process is similar to the one proposed by Kappes et al. (2012), who assigned different scores to each value that each indicator could attain. These scores (here named weights) could take values between 0 and 1 to show how a value (i.e. proxy variable) contributes to the vulnerability of an element at risk. For example, a single-floor building is always more vulnerable (score=1) than a two-floor building (score=0.5) (Kappes et al., 2012). This perspective is adequate for the static representation of physical (i.e. built environment) vulnerability but cannot represent the dynamic nature of the human vulnerability. Since people are not static but they move across time and space the importance of the variables related to the individuals have to integrate the variability of indicators through places across the day (Table 3). For example, young people between 20-65 years old take the highest weight of vulnerability (e.g. w=1) during day-rush hours but a lower weight (e.g. w=0.5) during night-rest hours when old people take the highest weight. So far, there is no study that performs such a dynamic mapping of vulnerability to flash floods. To do so, several vulnerability maps have to be created using e.g. a GIS software to calculate the vulnerability score of each proxy in space at different time increments (e.g. day-working hours, day-rush hours, night-rest hours, holidays e.c.t.).

The second weighting process assigns an importance to each indicator according to the purpose of each study. At this step, the importance (i.e. weight) of each indicator depends on how useful is a specific indicator for the vulnerability assessment in a study area. For example, emergency managers could assign weights to the indicators according to their relevance for successful evacuation (e.g. the number of buildings floors or the physical ability of individuals are of high importance) (Kappes et al., 2012). Deciding what indicators to include and with which level of importance is a difficult task which is not included in most of the vulnerability studies (Cutter et al., 2000; Chakraborty et al., 2005; Whilhelmi and Morss, 2012). This type of weighting requires experts' judgment as well as documentation of past events always considering the location-timing variability of vulnerability indicators (paragraph 4.2.2).

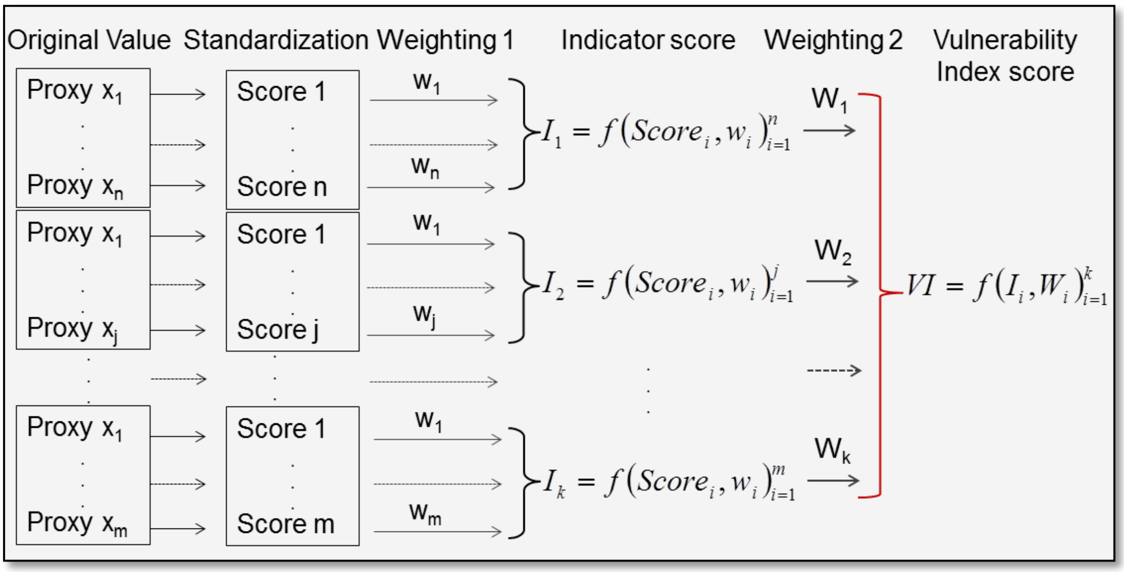


Figure 4. Flash flood vulnerability computational model.

Vulnerability computation presented in Figure 4 involves many challenges. Future work has to deal with the following questions:

1. How can we make the different sources of data compatible and comparable?

2. How can we achieve finer spatial resolution at our analysis?
3. How can we introduce the variation of the metrics within the spatial-temporal context of flash flooding?

The first question explains the difficulty to combine data with different measurement units in order to take a uniform metric of vulnerability. For example, number of old people has to be combined with number of the fragility of buildings. To deal with this difficulty, a standardization approach is needed to convert the original value of each proxy variable into a standardized (dimensionless) score. The difference of the present study with others that used standardization processes (Chakraborty et al., 2005; Whilhelmi and Morss, 2012) is that the resulted scores cannot be used directly as a metric of high or low vulnerability. This is because we also want to consider the positive contribution (coping capacity) of a proxy that would decrease the vulnerability of an element at risk. For example, Whilhelmi and Morss (2012) used residents over 65 years old as a variable that contributes always negatively to the vulnerability. This means that the vulnerability score indicates a high vulnerability if a big number of people over 65 years old lives in the area and a low vulnerability there are few people over 65 years old. This use of simplified and univocal variables as indicators could explain some of the failures of their study such as the inability to capture the high damages in the CSU campus. In our case, every proxy has to be converted in a dimensionless score without judging directly its influence on the final vulnerability. As mentioned above, for example, old people do not always constitute a high vulnerability proxy. Younger people are also highly vulnerable in some cases. Assigning a relative weight will indicate the final contribution of each proxy to the vulnerability score of each indicator.

Considering the spatial resolution of the analysis, the problem of the different resolution of each dataset has to be faced. Although the maximum flows in the study area can be simulated by the “Distributed Hydrological Model-Threshold Frequency” prediction tool at the scale of a grid-cell (e.g. 4x4 km) (Calianno et al., 2013), social information are not always available in such fine resolution. For example, the finest available resolution of the demographic data is the census block. This mismatch could be eliminated by rasterizing the computed vulnerability layers according to the flood layer grid (Azar and Rain, 2007).

The third question will be addressed by dealing with the time-space weighting processes described earlier in this paragraph. An average vulnerability score can be estimated for each time increment for the spatial extent of the study area. Thus, different maps would be produced with the relative vulnerability index score for different times. The flood potential map (raster layer) has to be overlapped by the vulnerability index scores from the computational vulnerability model to provide the final vulnerability assessment maps.

4.3.3. Limitations and uncertainties of the proposed vulnerability assessment

Uncertainty in vulnerability assessment and in natural risk analysis in general, can be separated in two types: (i) the inherent or stochastic uncertainty that resides from the randomness and the variability in human and natural environment (e.g. the gender of a random individual or the distribution of flash flood velocities) and (ii) the epistemic uncertainty that is related to our limited knowledge on physical and social processes and the lack of verification data related to in-situ behavioral response (e.g. the scarcity of information on human risk perception). The first type of uncertainty cannot be reduced. Epistemic uncertainty that involves statistical uncertainty (i.e. limited data) and model uncertainty can be reduced by putting efforts on data collection or research on models improvement (Ciurean et al., 2013). Of course, uncertainties exist and propagate in all stages of the assessment i.e. the introduction of input data, the model performance and the output results interpretations. Especially, the input data uncertainty occurs in the first step of the vulnerability assessment and propagates through the model and determines the final results. Thus, it is very important to collect reliable data. Underestimation of vulnerable population through the use of undercounted demographic data (e.g. population density) in the corresponding indicators is a problem that introduces uncertainty to the inputs (Azar and Rain, 2007). Also, a big challenge regarding the data of individuals is the collection of the cognitive and behavioral characteristics (e.g. the individual risk perception). To minimize this aspect of uncertainty advanced surveys including experts' and individuals' opinion have to be conducted with carefulness in every case study.

5. CONCLUSION AND PERSPECTIVE

Flash flood impacts present high variability and diversity from place to place not only due to differences in hydro-meteorological circumstances but also due to the space-time variability of people's exposure and capacity of reaction. Rapidness of flash floods that means short time between the peak of the excessive rainfall and the flood peak has a negative contribution on the available time for warning and protective actions including protection of movable belongings. This fact generates the need to examine vulnerability to this type of flooding separately.

The present study focuses on human-dependent characteristics and concepts that shape population and place vulnerability to this short-fuse and localized type of event. The term human-dependent yields the anthropogenic characteristics that are related to the natural and built environment as well as the social and behavioral aspects that influence the distribution of human-related impacts (e.g. loss of life, injuries e.c.t.). Factors that influence vulnerability of places and people to flash flooding are explored through the review of the literature on flash flood fatalities and damages. The main conclusion is that drowning is the main cause of death in most of the past flood events especially when it is related with vehicle-mobility into flashing waters. Thus, road network during the rush hours constitute the most vulnerable target to focus on. Risk-taking behavior and autonomy/flexibility to re-schedule the daily work-related activity are some of the most important drivers of the way people react during flooding. After that, factors are "converted" into specific indicators accompanied with proxy variables relevant for the case of flash flooding. Forty-eight flash-flood specific indicators are presented according to their relation with the identified vulnerability factors. This process is based on a critical synthesis of the analyzed factors and the review of studies on assessment and mapping of vulnerability to different natural hazards using indicators. An important advance of the present study in vulnerability assessment is the way in which the proposed indicators and proxies contributing to the vulnerability (i.e. increase or decrease) is not considered as constant. The variation of vulnerability depending on where and when flooding occurs is taken into account to enable the dynamic mapping of human vulnerability to a flash flood event.

The main contributions of this work to the flash flood vulnerability assessment can be summarized as follows:

- Construction of a conceptual vulnerability model suitable for the assessment of coupled physical and social vulnerability to flash floods.
- Incorporation of the knowledge on flash flood casualties into measurable variables and determination of their variability depending on their intersection with the flash flood event in space and time.
- Proposal of a GIS-based computational model for the integrated measurement and mapping of vulnerability to flash floods' spatial and temporal resolution.

The basic difficulties through this study are related to the limited available literature for the specific type of flash flood. In addition to that, the integration of human (i.e. social and behavioral) and physical attributes is a difficult task that requires deep understanding of the embedded processes where various uncertainties are hided.

Of course, this contribution does not constitute a final research product but it is based on continuing study on flash flood vulnerability assessment and the corresponding uncertainties. Next research steps in the near future should be the following:

- Test of the relevance of the whole set of the proposed indicators and proxies using different case studies. Data availability and uncertainty need to be explored.
- Performance of an advanced weighting of indicators and proxies based on experts' opinion survey. Local sensitivity analysis has to be conducted to test the sensitivity of such proxies in predicting the space-time distribution of impacts on the selected past events.
- Validation of the spatial vulnerability computational model based on the correlation between the vulnerability (High/Low) and the flood impacts (High/Low) of historic flash flood.

This research could be a useful pattern for future studies on the identification of vulnerable places and people to flash floods. Once a specific case study is under interest local experts' knowledge and relevant statistical analysis should be integrated in order to select the appropriate indicators. Depending on the quantity and type of the available data, the proposed proxy variables could be modified or simplified to adapt to the specific context of the case study. This study is a first step toward the tool that has been developed in order to answer the needs of flash flood forecasters to advance their prediction of flash flood impacts, but this study can also be useful for urban and emergency managers.

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